

Final Summary of Research Report

NASA Grant NAG5-13074

Project Title: **Probing the Relativistic Jets of Active Galactic Nuclei with
Multiwavelength Monitoring**

Institution: **Trustees of Boston University**


Principal Investigator: **Prof. Alan P. Marscher**

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Period Covered by Report: **March 15, 2003 to March 14, 2005**


University of Michigan

The work completed includes the analysis of observations obtained during Cycle 7 (March 2002–February 2003) of the Rossi X-ray Timing Explorer (RXTE). The project was part of a longer-term, continuing program to study the X-ray emission process in blazars and radio galaxies in collaboration with Dr. Ian McHardy (U. of Southampton, UK) and Prof. Thomas Balonek (Colgate U.).

There were no inventions under this grant during the reporting period.

The goals of the program are to study the X-ray emission mechanism in blazars and radio galaxies and the relation of the X-ray emission to changes in the relativistic jet. The program includes contemporaneous brightness and linear polarization monitoring at radio and optical wavelengths, total and polarized intensity imaging at 43 GHz with a resolution of 0.1 milliarcseconds with the VLBA, and well-sampled X-ray light curves obtained from a series of approved RXTE programs.

The objects studied in the time period covered by the grant were 3C 120, 3C 279, PKS 1510–089, and 3C 273, all with radio jets containing bright knots that appear to move at superluminal speeds. During RXTE Cycle 7, the project was awarded RXTE time to monitor PKS 1510–089 two times per week, 3C 273 and 3C 279 three times per week, and 3C 120 four times per week. In addition, 3C273 and 3C 279 were observed several times per day during a ten-day period in April 2002.

The X-ray data, including those from earlier cycles, were compared with radio measurements obtained in the centimeter-wave band by the monitoring program of Drs. Margo and Hugh Aller at the University of Michigan Radio Astronomy Observatory, monthly imaging observations with the VLBA at 43 GHz, and optical observations obtained at several telescopes around the world (Lowell Observatory; Torino U. Obs. and Perugia U. Obs., Italy; and Foggy Bottom Obs. of Colgate U.).

3C 120

The radio galaxy 3C 120 is a hybrid object, with a relativistic jet displaying apparent superluminal motion at $\sim 5c$, combined with Seyfert-like X-ray emission, including an iron emission line near an energy of 6 keV. Since the X-ray continuum of black-hole binary systems (“microquasars”) in our Galaxy is similar to that of Seyferts, the investigators set out to determine whether 3C 120 shares the remarkable behavior of the microquasar GRS 1915+105: X-ray dips followed by ejections of superluminal knots. As shown in Figure 1 and reported in Marscher et al. (2002, *Nature*, **417**, 625; and 2004, in *X-Ray Timing 2003: Rossi and Beyond*, AIP conf. Proc., **714**, 167), this is indeed the case: There are eight significant X-ray dips that precede the “time of ejection” (coincidence of the moving feature with the core at the narrow end of the radio jet) by ~ 60 days.

The X-ray dips in GRS 1915+105 are thought to be caused either by an instability breaking off a piece of the inner accretion disk, which then falls into the black hole, or by alignment of the magnetic field toward the polar direction. Each of these would cause a

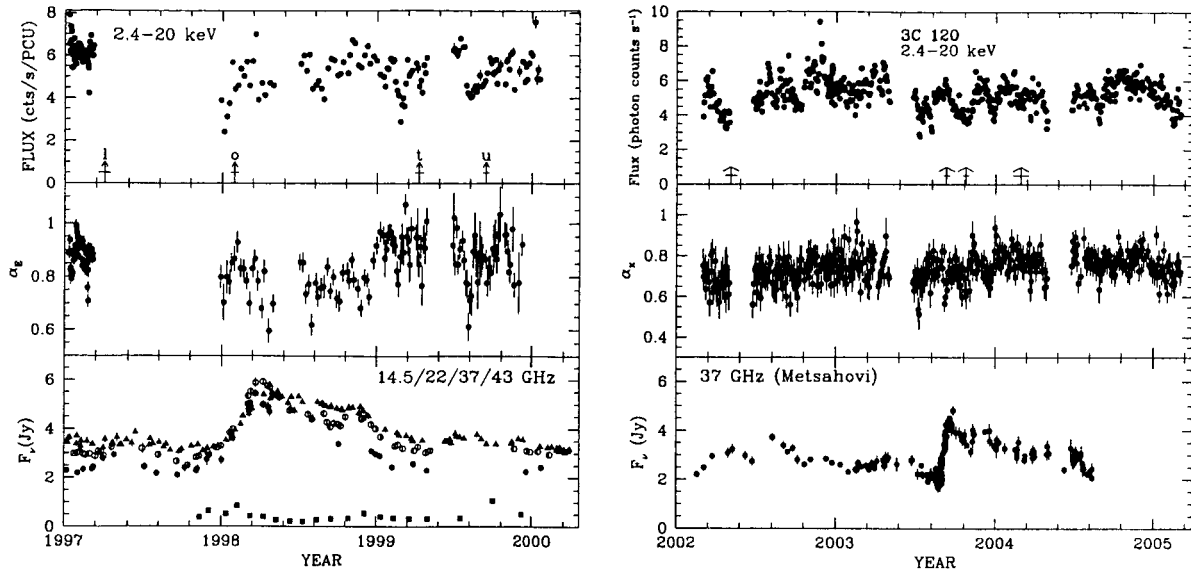


Figure 1. *X-ray light curve and variation of the X-ray spectral “energy” index of 3C 120. The times when a new, bright superluminal knot appeared at the radio core are marked by vertical arrows, with the uncertainties noted by horizontal bars.*

decrease in the energy converted to X-ray emission, accompanied by a burst of energy down the jet (actually, jets, since there is a counterjet made invisible by relativistic beaming). When this disturbance travels past the radio core, a superluminal knot is seen. The observed delay implies that the radio core is at least 0.4 pc downstream of the black hole. On a radio image, the angular distance between the two ~ 0.2 milliarcsec, projected on the plane of the sky. This constrains models of the innermost regions of relativistic jets, requiring either acceleration out to parsec scales or the presence of a region where energization of relativistic electrons is inhibited close to the black hole/accretion disk system.

PKS 1510–089

The $z = 0.361$ quasar PKS 1510–089 is an extreme member of the extreme class of blazars. The apparent speeds of its radio knots are as fast as $\gtrsim 30c$. Consistent with this, the variations in radio flux show little or no frequency-dependent time delay much of the time. This implies that opacity effects are relatively unimportant, as one might expect if knots move out of the core region so rapidly. The X-ray spectrum is flatter than most blazars, with the energy index α_E , where $F_\nu \propto \nu^{-\alpha_E}$ varying within the range 0 to 0.5. The mm-wave spectrum has a similar slope, so the X-ray spectrum is consistent with inverse Compton models.

Figure 2 displays the X-ray and radio light curves, with the dates of superluminal ejections marked. The correlation between the two light curves is highly significant, with a peak in the correlation function corresponding to a *reverse* (radio leads the X-ray) time lag of about 6 days. Such a reverse delay occurs only if the X-ray emitting region is *at or downstream of the radio core*. The investigators therefore conclude that the X-rays from PKS 1510–089 arise not from near the accretion disk, but from the radio-emitting part of the jet. In support

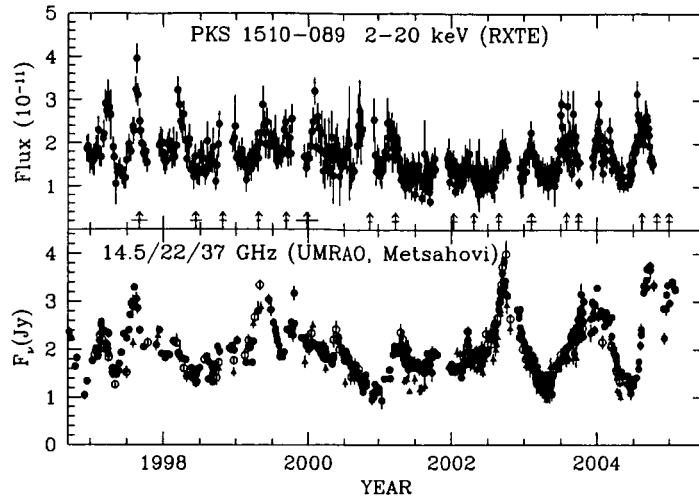


Figure 2. Multifrequency light curves of PKS 1510-089. The vertical arrows have the same meaning as in Fig. 1.

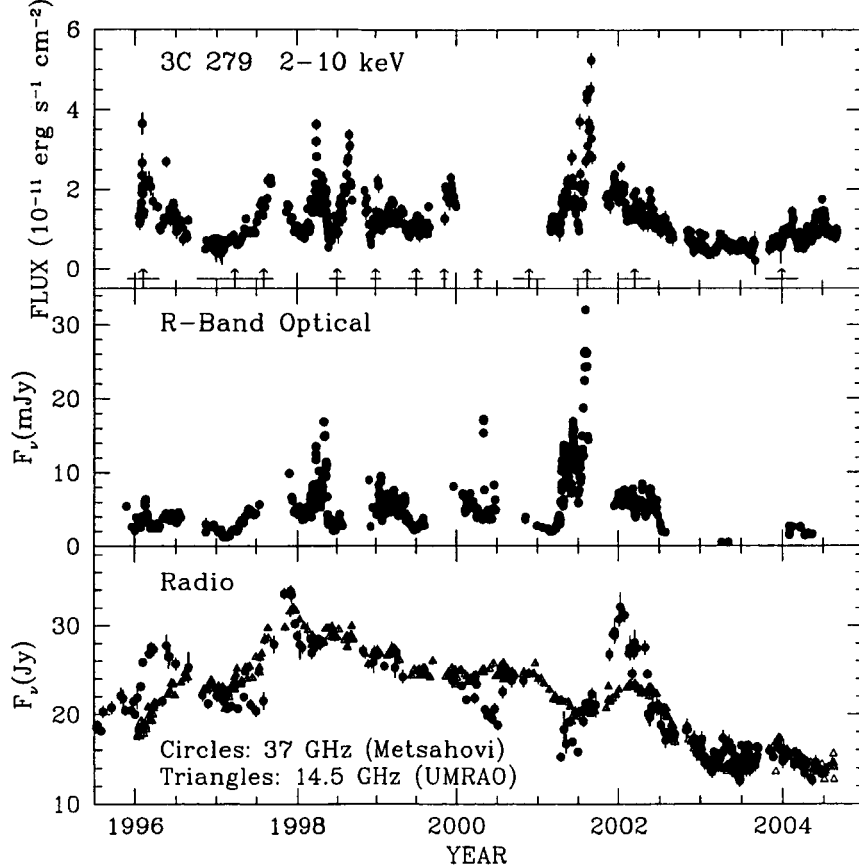


Figure 3. Multifrequency light curves of 3C 279. The vertical arrows have the same meaning as in Fig. 1.

of this interpretation, ejections of superluminal knots almost always occur near the epochs of X-ray flares.

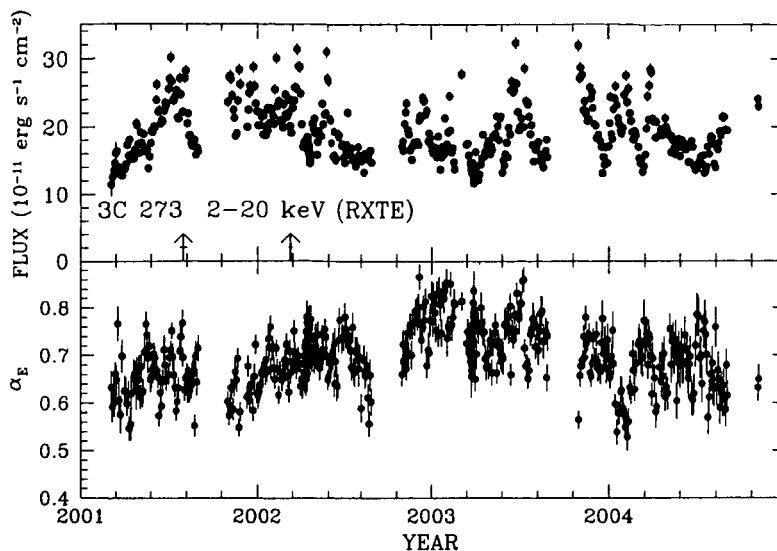


Figure 4. X-ray light curve and spectral index of 3C 273. The vertical arrows have the same meaning as in Fig. 1.

3C 279

Figure 3 shows the X-ray, optical, and radio light curves of the quasar 3C 279. As is apparent by eye as well as with a formal analysis, there is an excellent correlation between the X-ray and optical variations. The discrete cross-correlation function is peaked at 6 ± 6 days (optical leading the X-ray). There is a weaker—but still significant—correlation between the X-ray and radio total flux variations, but with the radio lagging by 100-200 days. This is expected owing to opacity effects in the radio as well as to an increase in the radio flux of many knots as they separate from the core. As with PKS 1510–089, there is a general correspondence between X-ray flares and superluminal ejections.

The close relationship between the X-ray, optical, and radio emission implies that nearly all the radiation observed in these blazars is relativistically beamed and produced in the jet. The investigators measured apparent speeds of radio knots as high as $25c$ (three times higher than typical in this object). This suggests that (1) the jet usually points closer to the line of sight than the angle that produces the highest apparent speed, and (2) the Lorentz factor of the jet flow is at least 25. This implies that the Doppler beaming factor exceeds 25 as well. This new high value explains why 3C 279 is among the most extreme blazars.

3C 273

Figure 4 shows the X-ray light curve of the quasar 3C 273. It undergoes fluctuations similar to those of 3C 120, and in fact a study of BeppoSAX data by Grandi and Palumbo (2004, *Science*, **306**, 998) concludes that the X-rays come from both the central engine and the jet. Analysis of the power spectral density of the variations by co-I McHardy gives a black-hole mass $\sim 3 \times 10^8 M_{\odot}$. We have not yet been able to draw a connection between the X-ray

variations and ejections of superluminal radio knots.

The following publications resulted from this project:

- Marscher, A.P., Jorstad, S.G., McHardy, I.M., Aller, M.F., Balonek, T.J., and Sokolov, A. "Where the Action Is: Multifrequency Monitoring and VLBA Imaging of 3C 273, 3C 279, PKS 1510–089, and BL Lac", 2002, *Bulletin of the American Astronomical Society*, **34**, 1246. Paper given at 201st American Astronomical Society Meeting, Seattle, WA, 5–9 Jan. 2003.
- Marscher, A.P., Jorstad, S.G., McHardy, I.M., Aller, M.F., Balonek, T.J., Villata, M., Raiteri, C.M., Ostorero, L., Tosti, G., and Teräsranta, H. "The Connection between X-Ray and Radio-Optical Emission in Blazars," 2003, in *High Energy Blazar Astronomy*, ed. L.O. Takalo and E. Valtaoja, *Astronomical Soc. Pacific Conf. Ser.*, **299**, 173–182.
- Sokolov, A., and Marscher, A.P. "A Theoretical Study of Multifrequency Variability in Blazar Jets," 2003 in *High Energy Blazar Astronomy*, ed. L.O. Takalo and E. Valtaoja, *Astronomical Soc. Pacific Conf. Ser.*, **299**, 153–156.
- Marscher, A.P. "The Impact of Recent Monitoring Studies on the Theory of Multiwaveband Variability of Blazars", 2003, *Bulletin of the American Astronomical Society*, **35**, 749. Paper given at 202nd American Astronomical Society Meeting, Nashville, TN, 24–29 May 2003.
- Aller, M.F. "Radioband Observations of Blazars", 2003, *Bulletin of the American Astronomical Society*, **35**, 749. Paper given at 202nd American Astronomical Society Meeting, Nashville, TN, 24–29 May 2003.
- Marshall, K., Miller, H.R., and Marscher, A.P. "The X-ray Power Density Spectrum of 3C 120," 2003, *Bulletin of the American Astronomical Society*, **35**, 759. Paper given at 202nd American Astronomical Society Meeting, Nashville, TN, 24–29 May 2003.
- Marscher, A.P. "Relativistic Jets in Blazars: Where the Action Is," 2003, in *Radio Astronomy at the Fringe*, ed. J.A. Zensus, M.H. Cohen, and E. Ros, *Astronomical Soc. Pacific Conf. Ser.*, **300**, 133–140.
- Aller, M.F., Aller, H.D., and Hughes, P.A. "Survey of Variability," 2003, in *Radio Astronomy at the Fringe*, ed. J.A. Zensus, M.H. Cohen, and E. Ros, *Astronomical Soc. Pacific Conf. Ser.*, **300**, 159–168.
- Marscher, A.P., Jorstad, S.J., Aller, M.F., McHardy, I.M., Balonek, T.J., Terasranta, H., and Tosti, G. "Relative Timing of Variability of Blazars a X-Ray and Lower Frequencies," 2004, in *X-Ray Timing 2003: Rossi and Beyond*, ed. P. Kaaret, F.K. Lamb, and J.H. Swank, AIP Conf. Proc., **714**, 167–173.
- Marshall, K., Ferrara, E.C., Miller, H.R., Marscher, A.P., and Madejski, G. "X-ray/Optical Variability of Akn 120 and 3C 120," 2004, in *X-Ray Timing 2003: Rossi and Beyond*, ed. P. Kaaret, F.K. Lamb, and J.H. Swank, AIP Conf. Proc., **714**, 182–185.
- Sokolov, A., and Marscher, A.P. "Modeling of Multifrequency Variability of Blazars," 2004, in *X-Ray Timing 2003: Rossi and Beyond*, ed. P. Kaaret, F.K. Lamb, and J.H. Swank, AIP

Conf. Proc., **714**, 198–201.

Jorstad, S.G., Marscher, A.P., McHardy, I.M., Makrides, K., Salem, D., Balonek, T.J., Kartaltepe, J., Aller, M.F., Larionov, V., Efimova, N., Raiteri, C., Villata, M., Kurtanidze, O., Gaskell, M., and Turler, M. “Multi-Frequency Monitoring of Three Gamma-Ray Quasars,” 2004, in *X-Ray Timing 2003: Rossi and Beyond*, ed. P. Kaaret, F.K. Lamb, and J.H. Swank, AIP Conf. Proc., **714**, 202–205.

Sokolov, A., Marscher, A.P., and McHardy, I.M. “Synchrotron Self-Compton Model for Rapid Nonthermal Flares in Blazars with Frequency-Dependent Time Lags,” 2004, *Astrophysical Journal*, **613**, 725–746.

Marscher, A.P. “Relationship between High-Frequency Emission and the Radio Jet in Blazars,” 2004, in *Future Directions in High Resolution Astronomy: The 10th Anniversary of the VLBA*, ed. J.D. Romney and M.J. Reid, *Astronomical Soc. Pacific Conf. Ser.*, in press.

Marscher, A.P., and Jorstad, S.G. “3C 120 and the Disk-Jet Connection,” 2005, in *AGN Variability from Radio to X-rays*, ed. C.M. Gaskell *et al.*, *Astronomical Soc. Pacific Conf. Ser.*, in press.

Jorstad, S.G., Marscher, A.P., Aller, M.F., and Balonek, T.J. “X-ray, Optical, and Radio Monitoring of Gamma-Ray Blazars,” 2005, in *AGN Variability from Radio to X-rays*, ed. C.M. Gaskell *et al.*, *Astronomical Soc. Pacific Conf. Ser.*, in press.

Marscher, A.P. “Are 3C 120 and Other Active Galactic Nuclei Overweight Microquasars?” 2005, in *From X-ray Binaries to Quasars: Black Hole Accretion on All Mass Scales*, ed. T. Maccarone, *Astrophys. Space Sci.*, in press.

Marscher, A.P. “The Relationship between Radio and Higher-Frequency Emission in Active Galactic Nuclei,” 2005, in *Multiband Approach to AGN*, ed. A. Lobanov, *Memorie della Societa Astronomica Italiana*, in press

Jorstad, S.G., and Marscher, A.P. “Highly Variable Apparent Speed in the Quasar 3C 279,” 2005, in *Multiband Approach to AGN*, ed. A. Lobanov, *Memorie della Societa Astronomica Italiana*, in press

Marscher, A.P. “Multiband Impressions of Active Galactic Nuclei,” 2005, in *Multiband Approach to AGN*, ed. A. Lobanov, *Memorie della Societa Astronomica Italiana*, in press

Sokolov, A., and Marscher, A.P. “External Compton Radiation from Rapid Nonthermal Flares in Blazars,” 2005, *Astrophysical Journal*, **629**, in press.

McHardy, I.M., Lawson, A., Newsam, A., Marscher, A., Sokolov, A., Urry, C.M., and Wehrle, A. “Simultaneous X-Ray and Infrared Variability in the Quasar 3C 273. II: Confirmation of the Correlation and X-Ray Lag,” 2005, *Monthly Notices of the Royal Astronomical Society*, submitted

Final Summary of Research Report: Subcontract Activity

Institution: **Regents of the University of Michigan**

Institutional Principal Investigator: **Dr. Margo F. Aller**

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Period Covered by Report: **March 15, 2003 to March 14, 2005**

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FINAL TECHNICAL REPORT for NAG5-13074 (subcontract from BU)

Project Director: Margo F. Aller (Alan Marscher, BU, project PI)

Institution: University of Michigan, Ann Arbor, MI 48109

Period Covered: 03/15/03 - 03/14/05

Title: Probing the Relativistic Jets of Active Galactic Nuclei with Multiwavelength Monitoring

This work represents a part of a longterm study of the X-ray flux variability of AGNs and includes funding for the reduction and analysis of data obtained during Rossi XTE cycle 7 (March 1, 2002- February 28, 2003). The goal of this project is to study the origin of X-ray emission by relating the temporal changes in X-ray flux via well-sampled RXTE monitoring data (observations 2-3 times per week) to changes in the total flux density at optical/IR and centimeter-to-mm radio wavelengths; to linear polarization variability; and to structural changes at VLBI scales in the radio jet. Specific targets for the study were 3C 120, 3C 273, 3C 279, and PKS 1510-089, sources known from previous observations to exhibit X-ray variability correlated with optical/IR and/or radio band activity. Both temporally well-sampled radio data from single dish observation and VLBA observations are required for correct interpretation of the radio variability because of the complex evolution of many co-existing radio knots in the radio jet in some of these objects. The data base obtained as a result of this work remains the best existing archival data set in the X-ray/radio bands for Blazars.

The broadband total flux density variability data obtained from the project were cross-correlated to obtain time delay information which serve as emission model tests, and the radio data were used to establish relations between X-ray flux amplitude and radio band changes; the latter include new outbursts in the single dish monitoring data, the ejection of new components in the inner radio jet, and changes in the jet nozzle direction. My specific duties were: 1) responsibility for radio monitoring of the targets in the centimeter band (14.5, 8.0, and 4.8 GHz) for integrated total flux density and linear polarization using the University of Michigan 26-meter paraboloid. The sampling was matched to that obtained in the RXTE observations (typically 2 times weekly at 14.5 GHz and once per week at 8 and 4.8 GHz); 2) participation in the analysis and interpretation of the combined broadband data; and 3) dissemination of the program results at conferences and astronomical meetings. An example of the radio monitoring data for the program source PKS 1510-089 is shown in Figure 1.

The scientific results are described in detail in the full technical report prepared by the project PI, A. P. Marscher. These include identification of a general long-term correlation between radio and X-ray variability in PKS 1510-089 which has changed in character from epoch to epoch (X-ray leading or trailing; no correlation). While based on the 2002 data only, a discrete cross-correlation analysis identified that the X-ray led the radio variations, with the full multi-year data set now available a reverse time delay with the radio leading the X-ray by 6-17 days is present. The relation between the emissions supports an interpretation in which the X-ray emission originates in the radio jet and in which the

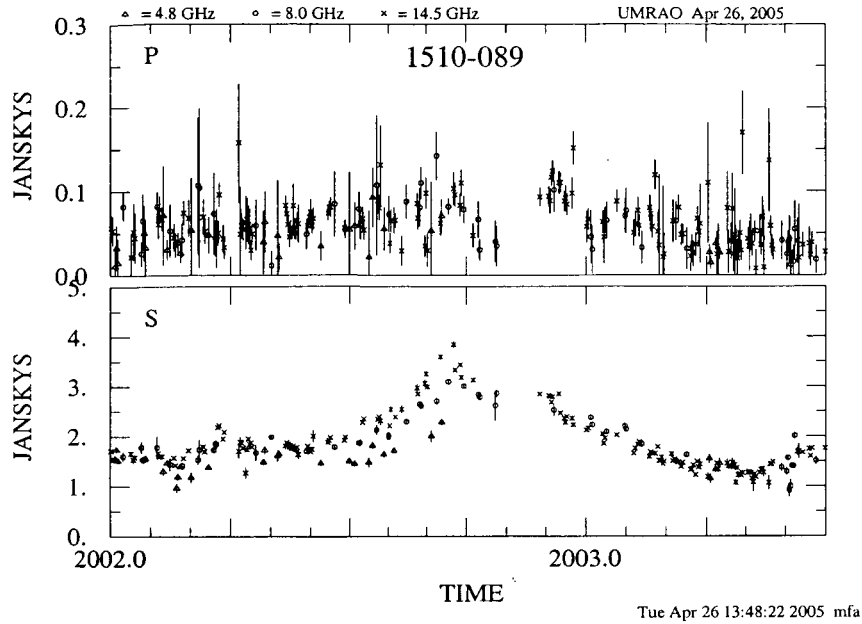


Fig. 1. Centimeter-band light curve for 1510-089 during cycle 7. The panels show from bottom to top daily averages of the total flux density and polarized flux. During this cycle a double-peaked event was captured in the radio light curves. The long gap in the observations at 4.8 GHz corresponds to the sun constraint time window when the source was too close to the sun for observation.

amplitude of this emission is related to radio jet changes. Additional results in which the radio data play a key role in the interpretation are those for 3C 120. Observations in cycle 7 provided further evidence for a correlation between dips in the RXTE light curves and time-delayed VLBI component ejections in this source, supporting the preliminary result reported in Nature (Marscher, A. P. , et al. Nature 417, 625, 2002). These data argue for a direct link between changes in the accretion disk and the radio jet.

No inventions were made by me as part of this work, and no equipment was purchased by me. Results from the program have appeared in several conference proceedings or been presented at AAS meetings (listing in Marscher report) with acknowledgments for NASA support.